

4. Multimodality Pilot Model for Visual and Motion Cues*

*R. L. Stapleford
Systems Technology, Inc.*

A preliminary model for pilot control behavior when utilizing both visual and motion cues is presented. The model is based on a detailed review of all known data, including some unpublished data from recent experiments conducted by NASA-ARC and STI. Models for the three feedback paths (visual, angular motion, and linear motion) and integration of the various feedbacks are described.

INTRODUCTION

This paper presents an initial hypothesis for a multimodality pilot model, i.e., an approximate mathematical description of pilot control behavior when utilizing both visual and motion cues. Because there are many gaps in the currently available experimental data, certain portions of the model can be only vaguely defined. Future experiments may provide the basis for subsequent refinements and modifications. In the meantime, this preliminary model is meant to serve as a working hypothesis.

The primary motion-sensing mechanisms in a normal human are the vestibular organs—the semicircular canals and the utricles (ref. 1). The semicircular canals respond to angular and the utricles to linear accelerations of the head. There are three essentially orthogonal canals on each side of the head, so that angular accelerations with any direction can conceivably be sensed. The two utricles, on the other hand, are approximately coplanar and thus respond only to a component of the total linear acceleration.

The basic structure of the multimodality pilot model consists of three parallel feedback paths as shown in figure 1. This figure is drawn for a compensatory attitude control task, i.e., visual display is attitude error. Modifications to the visual path for other tasks or displays are obvious. It is recognized that the three noninteracting feedback paths are a gross simplification. Interactions between the visual and vestibular systems occur at several levels. At one level are the compensatory eye motions produced by the vestibular system when the head is moved. At another level are the illusions and disorientations resulting from conflicting visual and vestibular sensations. However, for the purposes of this paper the simplified model is adequate.

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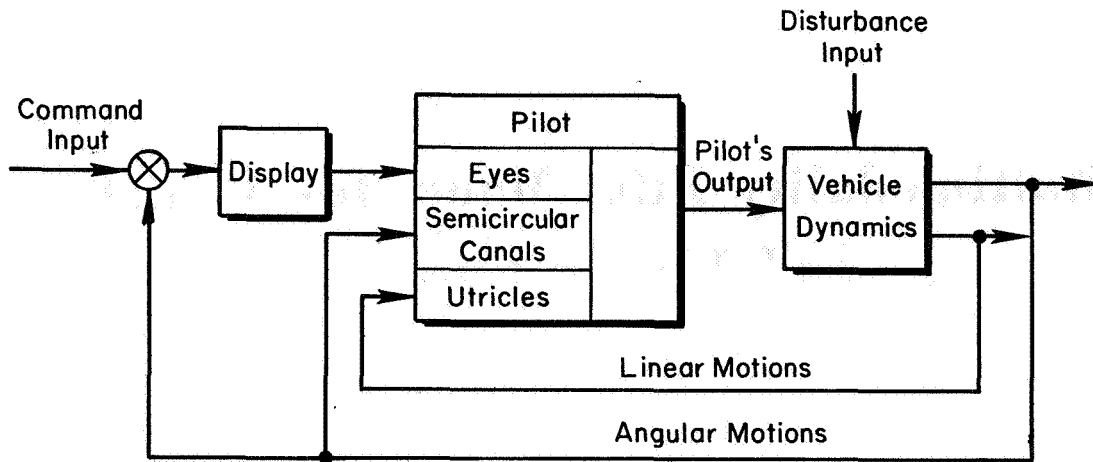


Figure 1. —Basic structure of multimodality pilot model.

The characteristics of the individual pathways of figure 1 are discussed in the next section. Later, the integration of the three feedbacks is considered. From an examination of the available data on the effects of motion cues, the conditions under which the various feedbacks are utilized are hypothesized.

CHARACTERISTICS OF INDIVIDUAL PATHWAYS

VISUAL. —Characteristics of the visual path are well known. A quasi-linear model for control tasks involving only visual cues is described in detail in reference 2. This description includes a describing function model form and adjustment rules for selecting the variable parameters. Possible modifications of the visual path due to the presence of motion cues will be discussed later.

SEMICIRCULAR CANALS. —While the semicircular canals are basically responsive to angular accelerations, their dynamic characteristics are such that over the range of frequencies normally used in manual control they can be considered as rate gyros that provide the pilot with a subjective impression of angular velocity. The model for the semicircular canal path can be represented by the elements shown in figure 2. The sensor is comprised of the semicircular canals which provide the subjective angular velocity. As in the case of visual feedback it is assumed that the pilot can provide some equalization on the sensed quantity. The final element shown in figure 2 is a lag that includes the net effects of any central processing, transmission, and neuromuscular lags. Portions of this lag are common to all three feedback paths. The characteristics of each of the three elements in figure 2 will now be discussed.

A great deal of research has been done on the sensory characteristics of the semicircular canals. A thorough summary of this work is given in reference 1. A model of semicircular canal dynamics that is particularly convenient for application to control system analyses is that shown in figure 3. Numerous experiments have demonstrated that the

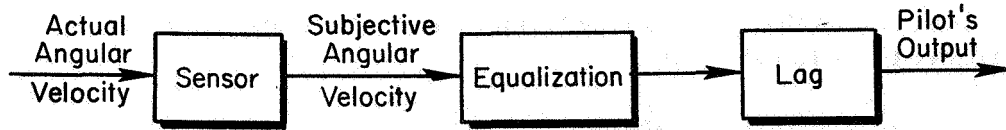


Figure 2.—Elements of the semicircular canal path.

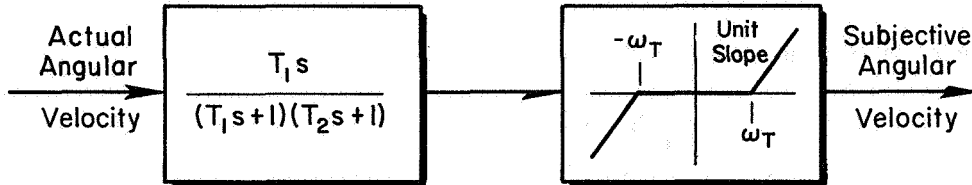


Figure 3.—Semicircular canal dynamics.

numerical values for the parameters in figure 3 have considerable intersubject variability and are a function of the axis of rotation (ref. 1). Many of these experiments have dealt with the larger time constant, T_1 . From this work the estimated values for pilots are (ref. 1):

$$T_1 \doteq \begin{cases} 6.5 \text{ sec for roll} \\ 5.3 \text{ sec for pitch} \\ 8.0 \text{ sec for yaw} \end{cases} \quad (1)$$

Data for the shorter time constant, T_2 , are much more limited. The best estimate is (ref. 1).

$$T_2 \doteq 0.1 \text{ sec for any axis} \quad (2)$$

Thus, the linear element in figure 3 acts like a bandpass filter with low-frequency cutoff at 0.125 to 0.15 rad/sec and high-frequency cutoff at 10 rad/sec, and with nearly unity gain over the frequency range 0.3 to 5 rad/sec. Over this range the semicircular canals function as a rate sensor.

Numerical values for the threshold shown in figure 3 are based on experiments to determine the minimum detectable constant angular acceleration or step velocity change. For a step acceleration input of magnitude α , the output of the linear element in figure 3 would be

$$T_1 \alpha \left[1 - \left(\frac{T_1}{T_1 - T_2} \right) e^{-t/T_1} + \left(\frac{T_2}{T_1 - T_2} \right) e^{-t/T_2} \right]$$

The steady-state response is then $T_1\alpha$. The minimum detectable angular acceleration, $\alpha_{\min}$, is then related to the threshold by

$$T_1\alpha_{\min} = \omega_T \quad (3)$$

Using the $\alpha_{\min}$ values from reference 3, i.e.,

$$\alpha_{\min} = \begin{cases} 0.5 \text{ deg/sec}^2 & \text{for roll or pitch} \\ 0.14 \text{ deg/sec}^2 & \text{for yaw} \end{cases} \quad (4)$$

and the time constants from equation 1, the threshold is estimated to be

$$\omega_T = \begin{cases} 3.2 \text{ deg/sec} & \text{for roll} \\ 2.6 \text{ deg/sec} & \text{for pitch} \\ 1.1 \text{ deg/sec} & \text{for yaw} \end{cases} \quad (5)$$

As a matter of interest, these thresholds are an order of magnitude greater than those that would be specified for flight control system rate gyros.

The above expression can also be used to approximate the latency time (time to detect an input acceleration), T_L , by

$$\begin{aligned} \omega_T &= T_1\alpha \left[1 - \left(\frac{T_1}{T_1 - T_2} \right) e^{-T_L/T_1} + \left(\frac{T_2}{T_1 - T_2} \right) e^{-T_L/T_2} \right] \\ &\doteq T_1\alpha \left(1 - e^{-T_L/T_1} \right) \end{aligned} \quad (6)$$

Equation 6 has been shown to match measured latency times quite accurately, e.g., reference 3.

Values for the threshold can also be estimated from the minimum detectable step change in velocity. For a step velocity change of magnitude, ω , the output of the linear element of figure 3 is

$$\frac{T_1\omega}{T_1 - T_2} \left(e^{-t/T_1} - e^{-t/T_2} \right)$$

The maximum value of the output is easily shown (using $T_1 \gg T_2$) to be approximately ω . Therefore the threshold, ω_T , is also approximately equal to the minimum detectable step velocity change. Threshold estimates obtained in this manner are in rough agreement with those given in equation 5, although there is considerable intersubject variability. (See ref. 1 for a more complete discussion of this subject.)

In most cases of manual vehicular control, the motions are considerably above the thresholds noted above and the primary concern is in the frequency range of 1 to 5 rad/sec. Then the sensor dynamics for the semicircular canal path are adequately approximated by

$$\frac{\text{subjective angular velocity}}{\text{actual angular velocity}} = \frac{1}{T_2 s + 1} = e^{-T_2 s} \quad (7)$$

* The other two elements in the semicircular canal path are equalization and lag. Unfortunately, there are no direct data on these two and there is only a limited amount of inferential data. Some of the data of reference 4 indicate that relatively large lead equalization (roughly 1 second) is possible. Whether or not the pilot can generate lead equalization as large as that measured for visual tracking is unknown. In fact, the mechanism for generating lead in visual tasks is still not completely understood. Until more concrete data can be obtained, it will be hypothesized that the lead in the semicircular path can be as large as that used in the visual path.

It is also theoretically possible for the pilot to use lag equalization in the semicircular path. However, as will be covered later, the primary function of the path appears to be to supply lead equalization. In none of the cases considered to date has lag equalization been desirable. Therefore, it is assumed that the semicircular canal equalization is of the form $K_1(T_3 s + 1)$.

As indicated above, there are no direct data on the lag element. Preliminary results from some recent experiments (ref. 5) indicate a lag of roughly 0.1 second. Completion of the detailed analyses may allow a refined estimate of the time delay, but for now a value of 0.1 second will be assumed.

Combining the above gives the model for the semicircular canal path shown in figure 4.

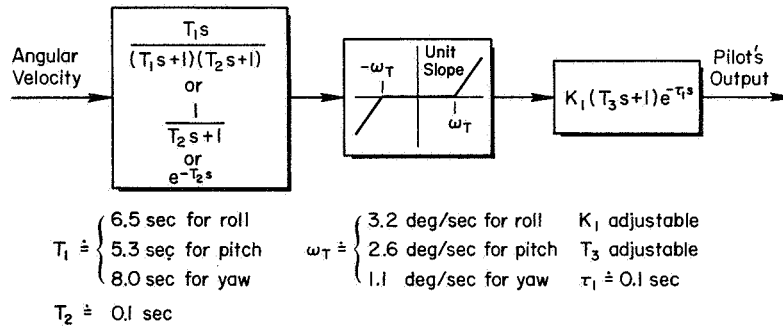


Figure 4.—Model for semicircular canal path.

UTRICLES

The model for the utricular path consists of three elements similar to those used for the semicircular path—sensor, equalization, and lag. While little data is available on the sensor dynamics of the utricles, it is widely accepted that they are sensitive to linear accelerations in the plane of the utricular maculae. This plane is inclined front end upward approximately 30° from the horizontal in the upright head.

It should be noted that, like conventional accelerometers, the utricles do not respond to inertial accelerations but to the total applied force. For example, on the ground the utricles respond to tilting the head relative to the gravity vector just as an accelerometer attached to the head would. For simplicity, the inputs to the utricles will hereafter be referred to as accelerations. However, the reader should remember that this means the accelerations that would be sensed by an accelerometer.

The most recent data on utricular sensory dynamics is that given in reference 6. That report suggests a model for the sensory dynamics of the form

$$\frac{\text{subjective acceleration}}{\text{actual acceleration}} = \frac{(T_5/T_4)(T_4s+1)}{(T_5s+1)(T_6s+1)} \quad (8)$$

where

$$T_4 \doteq 13 \text{ sec}$$

$$T_5 \doteq 5.2 \text{ sec}$$

$$T_6 \doteq 0.67 \text{ sec}$$

Over the frequency range of interest in most vehicular-control situations equation 8 can be adequately approximated by

$$\frac{\text{subject acceleration}}{\text{actual acceleration}} \doteq \frac{1}{T_6s+1} \quad (9)$$

The utricular threshold is so small, on the order of 0.01g or less, that it will have a negligible effect in most vehicular control situations. There are also very few data on latency times but reference 3 does show latency times on the order of 1 second for accelerations of 0.1g.

Information on the equalization and lag elements is limited to the reference 7 analysis of some of the data from reference 3. The results for the one case involving a utricular feedback indicated the presence of a first-order lead at 3 rad/sec and a time delay of 0.3 second. The lead is identified as pilot equalization and the time delay as the low-frequency approximation to the dynamics of the lag element. This analysis provides some evidence to support the inclusion of pilot adjustable lead in the utricular path. However, there are no data on the adjustable range of the lead or the possibility of lag equalization. The possible desirability of lag equalization cannot be ruled out because of the extremely wide range of acceleration numerator zeros that can occur in vehicle transfer functions. These zeros are strong functions of the vehicle stability and control properties and the pilot's location. It is, at least theoretically, possible that in some cases lag equalization would be helpful.

The assumed model for the utricular path is shown in figure 5.

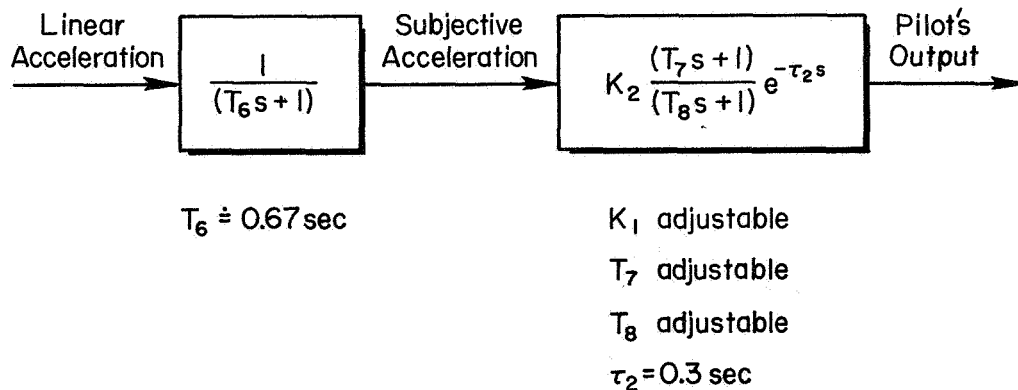


Figure 5.—Model for utricular path.

FEEDBACK INTEGRATION

The main objective here is to determine how the three feedback paths are combined and integrated by the pilot. We will start with a review of the available data and then postulate a general model. Experimental data that include pilot describing function measurements will be discussed first.

Table 1 summarizes those experiments in which pilot describing functions were measured for both fixed-base (visual-only tracking) and moving base or flight. In all cases the describing functions were measured from the displayed error to the pilot's control output. Consequently, the moving-base or flight results contain the effects of the parallel visual and motion feedbacks.

For one reason or another, the results of the first four references listed in table 1 are inconclusive when attention is centered only on motion effects. A limited amount of data is provided by references 3, 12, and 13, but Shirley (ref. 4) and NASA/STI (ref. 5) provide extensive experimental results of a highly complementary nature.

Shirley measured describing functions for 40 different controlled elements with and without motion cues. The motion cues resulted from rolling about a fixed horizontal axis with the subject's head nearly on the axis.

The NASA/STI tests used only 3 controlled elements but examined changes in the motion cues. Both roll and lateral position motions were used to simulate different head positions relative to the vehicle c.g., and a variety of washouts were tested. In addition to overall describing function measurements, similar to those made by Shirley, some unique experiments were conducted using two inputs in an attempt to measure the visual and motion feedbacks separately.

As the analyses of the NASA/STI results are not yet complete, a detailed comparison with Shirley's results cannot be made. A preliminary comparison indicates many similarities and several differences. As there were a number of dissimilarities in the experimental setups that could account for the differences in the results, we will concentrate here on the results which are in agreement. Both tests, as well as those of Meiry (ref. 3) and Newell (ref. 12 or 13), show that the major effects of motion cues are to increase pilot gain and reduce his high-frequency phase lags. The lead information supplied by the motion reduces the phase lag in the overall (combined visual and motion paths) describing function by an amount that is generally equivalent to a time delay reduction of 0.1 to 0.2 sec. As a result the pilot can, and does, increase his gain and crossover frequency to maintain similar, and frequently smaller, phase margins. The increase in crossover frequency is typically on the order of 1 rad/sec.

The two input data from the NASA/STI experiments are also providing information on changes in the visual feedback when motion cues are present. The low-frequency gain in the visual path is increased, less lead is used, and the time lag may be increased. With the lead provided by the motion cues, the pilot need not supply as much lead in the visual path and can allow his delay to increase. Because the motion feedbacks provide more lead than the visual feedback, the motion paths are dominant (have higher gain) at the higher frequencies, and the visual path dominates at lower frequencies. The two are of comparable magnitude in the region of 2 to 4 rad/sec. It also appears that the semicircular canal path is always utilized to a significant degree but that the utricular path is used only when the linear acceleration is a desirable feedback.

Newell's data (ref. 12 or 13) demonstrate the important difference between motion effects with a command or a disturbance input (see fig. 1 for the difference between a command and a disturbance input). Newell found that with a command input and a compensatory display, the in-flight describing functions were approximately the same as those for the

TABLE 1. -- DESCRIBING FUNCTION DATA

REF.	MOVING-BASE DEVICE	DISPLAY		MOVING-BASE INPUT	RESULTS	REMARKS
		FIXED- BASE	MOVING BASE			
8	Princeton Navion	CRT	CRT	Command	Flight τ 's higher by 0.1 - 0.2 sec than ground. Pilot's longitudinal gain in flight approximately 1/2 ground value.	Differences observed may not be totally due to motion differences because: 1. Different subjects for in-flight and ground data. 2. Considerable dis- tractions during in-flight tests.
9	NASA TV-2	Gyro horizon	Gyro or natural horizon	Disturbance	Inconclusive. Amplitude and phase differences were inconsistent.	Data reduction incorrect. Used error rather than input, cross-spectra.
10	Air Force Variable- Stability T-33	Gyro horizon	Natural horizon	Disturbance	Only conclusive dif- ference was lower gain on ground for frequen- cies less than approxi- mately 0.3 rad/sec	Considerable variability in the flight data.
11	MIT Any-Two- Degree of Angular Freedom Motion Simulator	CRT	CRT	Disturbance	Moving-base gains lower and lags larger than fixed-base.	Author attributes dif- ferences to a combination of "simulator nonlinear- ities, a poorly-marked and less sensitive moving- base display grid, and perhaps vestibular con- fusion and insensitivity to very small deflec- tions."

TABLE 1. -- CONCLUDED

REF.	MOVING-BASE DEVICE	DISPLAY		MOVING-BASE INPUT	RESULTS	REMARKS
		FIXED- BASE	MOVING- BASE			
3	MIT Any-Two- Degrees of Angular Freedom Motion Simulator	CRT	CRT	Disturbance	1. With visual and semi-circular canal stimulus, τ reduced 0.1 sec from visual alone. 2. With semicircular canal and utricular stimuli, τ reduced 0.2 sec and crossover frequency twice that for visual alone.	Case 1 was rotation about vertical axis. Case 2 was rotation about horizontal axis. Results further analyzed in Ref. 7.
12, 13	Air Force Variable- Stability T-33	Gyro horizon	Gyro or natural horizon	Command or disturbance	1. Small differences between ground and flight with command input. 2. Flight with disturbance input had significantly higher crossover frequencies and lower τ 's than ground.	For flight tests, gyro horizon always used with command input and natural horizon always used with disturbance input. Compensatory display used for command inputs.
4	MIT Any-Two- Degrees of Angular Freedom Motion Simulator	CRT	CRT	Disturbance	Describing functions and performance measures given for 40 controlled elements. Generally, the addition of motion significantly increased the pilot gain, reduced high frequency phase lags, and improved performance.	Motion was roll about a horizontal axis with subject's head nearly on the axis.
5	NASA-ARC Six-Degree- of-Freedom Simulator	Gyro horizon	Gyro horizon	Disturbance (some tests with 2 inputs)	1. Similar to Ref. 4 for comparable controlled elements 2. Direct measurements of visual and motion feedbacks separately.	1. Motion was roll and lateral position. 2. Simulated head position and washouts were varied.

ground tests. In hindsight, this is not surprising. With a command input and compensatory display, the sensed motions are not the same as the visual display. The pilot senses the actual motion of the aircraft but sees the difference between that motion and the input. Thus, one might expect the pilot to ignore the motion cues and operate strictly on the visual cues. On the other hand, with a disturbance input the sensed motions and the visual display agree. The increase in crossover frequency and reduction in effective time delay found by Newell in this case agree quite well with the results of references 3, 4, and 5.

Unfortunately, Newell's results cannot be conclusively attributed to motion cue effects alone as there was also a difference in the display. The ground and flight tests with a command input utilized a gyro horizon display, while for flight with the disturbance input the natural horizon was used. Newell in references 12 and 13 attributes the changes in pilot characteristics to the improved display. However, since the results do check with those obtained in three other experiments, it appears likely that most of the differences were due to the pilot's utilization of the motion cues.

A literature survey on the effects of motion clues on pilot performance was also made for any additional clues on how or when a pilot utilizes motion feedbacks. Unfortunately, we could find only five experiments that met all of the following criteria: the pilot's task involved tracking, vehicle dynamics and the display were nearly identical for the fixed-base and moving-base tests, the motion simulator did not introduce significant spurious cues, and performance data were given. The five are references 3, 4, 5, 14, and 15. The performance data, however, do not prove very enlightening. There are several apparent discrepancies among these five tests. These discrepancies may be due to differences in: the training and experience of the subjects, the visual display, the magnitude and bandwidth of the input, or the manipulator. Nevertheless, two noteworthy results were found.

The reference 14 experiments showed that a pilot can utilize motion cues with a command input if he has a pursuit display. This finding is completely compatible with the previous conclusions on display-input effects. With a pursuit display the pilot can visually perceive the same vehicle motions he senses via his vestibular system. Since the two agree he can use both.

The reference 15 experiments demonstrated the importance of the training and experience of the subjects. These tests involved the simulated roll angle and lateral position control of a hovering helicopter. Two experienced helicopter pilots could not control the vehicle fixed base, but could moving base. Yet, two of three nonpilot subjects did better fixed base than moving base.

Based on the experimental data discussed above, the following hypotheses regarding the utilization of motion cues are made:

- (1) Motion cues cannot be used and will be ignored when tracking a random-appearing¹ command input with a compensatory display.
- (2) With any input-display combination except that indicated in (1), motion cues may be utilized.
- (3) The addition of motion cues will greatly enhance performance when considerable lead equalization and/or effective-time-delay reduction in the visual feedback would be beneficial.
- (4) With motion cues the gain in the visual path may be considerably increased over what it would be for fixed-base operation, the lead may be reduced, and the effective time delay increased.

¹With a simple, predictable input the pilot may be mentally able to separate the input and the vehicle response and to operate as if he had a pursuit display.

(5) The motion feedbacks will dominate at high frequencies, the visual feedback will dominate at low frequencies, and they will be of comparable magnitude in the region of 2 to 4 rad/sec.

(6) The utricular path will not be used unless the linear acceleration feedback is more favorable than the semicircular canal feedback.

These hypotheses plus the models for the semicircular canal and utricular paths (figs. 4 and 5) form the preliminary multimodality pilot model.

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